

Contribution of Increased Agulhas Leakage to Tropical Atlantic Warming

JOKE F. LÜBBECKE, JONATHAN V. DURGADOO, AND ARNE BIASTOCH

GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

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ABSTRACT

The upper tropical Atlantic Ocean has markedly warmed since the 1960s. It has been shown that this warming was not due to local heat fluxes and that the trade winds that drive the coastal and equatorial upwelling have intensified rather than weakened. Remote forcing might thus have played an important role. Here, model experiments are used to investigate the contribution from an increased inflow of warm Indian Ocean water through Agulhas leakage. A high-resolution hindcast experiment with interannually varying forcing for the time period 1948–2007, in which Agulhas leakage increases by about 45% from the 1960s to the early 2000s, reproduces the observed warming trend. To tease out the role of Agulhas leakage, a sensitivity experiment designed to only increase Agulhas leakage is used. Compared to a control simulation, it shows a pronounced warming in the upper tropical Atlantic Ocean. A Lagrangian trajectory analysis confirms that a significant portion of Agulhas leakage water reaches the upper 300 m of the tropical Atlantic Ocean within two decades and that the tropical Atlantic warming in the sensitivity experiment is mainly due to water of Agulhas origin. Therefore, it is suggested that the increased trade winds since the 1960s favor upwelling of warmer subsurface waters, which in part originate from the Agulhas, leading to higher SSTs in the tropics.

1. Introduction

Ocean temperatures are rising globally because of enhanced greenhouse gas emissions, but the trend is neither spatially nor temporally homogenous. Understanding the local warming patterns is important, as they have consequences for changes in ocean circulation and regional climate (e.g., Vecchi and Soden 2007; Xie et al. 2010; Collins et al. 2010; Dai 2011).

Tropical Atlantic sea surface temperatures (SSTs) have increased since the 1960s, in particular in the eastern part of the basin (Tokinaga and Xie 2011; Servain et al. 2014). As this warming was not directly forced by local heat exchange with the atmosphere (Servain et al. 2014), it is likely related to ocean–atmosphere dynamics. The tropical Atlantic is characterized by the north- and southeasterly trade winds converging slightly north of the equator at the intertropical convergence zone (ITCZ), leading to the presence of a warm pool in the western part of the basin and upwelling regions in the eastern equatorial basin and along the coast of North and southwestern Africa. While

the warming trend in the last decades is most pronounced in these equatorial and coastal upwelling sites, the wind stress that drives the oceanic upwelling has increased rather than decreased (Servain et al. 2014). This trend in the local winds should favor decreasing surface temperatures, as in the tropical Pacific Ocean, where the intensification of the trade winds was indeed accompanied by a cooling trend in the eastern equatorial basin over the last 15 years, as dynamically expected (e.g., McPhaden et al. 2011; Lübbecke and McPhaden 2014). The inconsistency between local winds and SST trends in the tropical Atlantic suggests that remote forcing might have contributed to the warming trend there.

In this study, we explore the possibility that remote forcing from outside the tropical Atlantic Ocean, namely, because of increased Agulhas leakage transport south of Africa (Rouault et al. 2009; Biastoch et al. 2009), has led to the warming of the subsurface tropical Atlantic. These tropical Atlantic subsurface waters, which are warmer than in previous decades, are subsequently upwelled to the surface by the increased trade winds, resulting in the observed warming trend at the surface.

As part of the global overturning circulation, warm Indian Ocean waters reach the South Atlantic via the Agulhas Current system south of Africa (Beal et al. 2011). A large portion of the Agulhas Current retroflects

Corresponding author address: Joke F. Lübbecke, GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany.
E-mail: jluebbecke@geomar.de

back into the Indian Ocean (Lutjeharms 2006). From the retroflexion, Agulhas rings are shed and propagate into the South Atlantic. The part of the transport that actually stays in the Atlantic and spreads northward is termed Agulhas leakage. The strength of Agulhas leakage is controlled by the intensity and location of the Southern Hemisphere westerlies (Durgadoo et al. 2013). In response to changes in those winds, model hindcast simulations suggest that Agulhas leakage increased over the past decades (Biastoch et al. 2009; Durgadoo et al. 2013). Trends in sea surface height show an increase in eddy kinetic energy in the Agulhas retroflexion region, which has been used as an indicator of increase in Agulhas leakage (Backeberg et al. 2012). However, analyses with ocean models point out that the non-eddy part also plays an important role for the amount of Agulhas leakage (Loveday et al. 2015). Rühls et al. (2013) found that about half of Agulhas leakage water is advected into the North Atlantic, and about 40% reaches as far as the northern subtropics.

A link between Agulhas leakage and upper-ocean heat content in the Atlantic Ocean north of 30°S has previously been suggested. In a coarse-resolution ocean–sea ice model, Lee et al. (2011) reported that an enhanced heat transport south of Africa has contributed to an increase in upper-ocean heat content in the Atlantic since the 1950s. Haarsma et al. (2011) showed in an idealized model study that, in response to an interruption of Agulhas leakage, a cooling signal is advected into the South Atlantic by ocean currents and reaches the western boundary after about 7–8 years, a time scale that is in agreement with Rühls et al. (2013). The signal then spreads to the eastern equatorial Atlantic in less than a year. Building on these results, we here use high-resolution model simulations, among them a sensitivity experiment that simulates an isolated increase in Agulhas leakage, to explicitly link variations in the strength of Agulhas leakage transport to temperature changes in the tropical Atlantic Ocean in order to explain their role in the observed tropical Atlantic SST trend. The remainder of the paper is organized as follows: The datasets and model experiments are introduced in section 2. The results from the hindcast as well as the sensitivity experiment are presented in section 3 and are summarized and discussed in section 4.

2. Datasets, model experiments, and methodology

a. Observational datasets

We use SSTs from the NOAA Extended Reconstructed SST (ERSST) version 3b dataset provided by the NOAA/OAR/ESRL Physical Sciences Division

(PSD) in Boulder, Colorado, United States (Smith et al. 2008). Subsurface temperatures are taken from the EN4 quality-controlled subsurface ocean temperature and salinity profiles and objective analysis dataset (Good et al. 2013) provided by the Met Office Hadley Center (<http://www.metoffice.gov.uk/hadobs/en4/>). For both datasets, we use information for the time period 1960–2007 at monthly resolution.

b. Model experiments

Outputs from three different experiments of the global nested ocean–sea ice INALT01 model are analyzed in this study (Durgadoo et al. 2013). INALT01 is based on the Nucleus for European Modelling of the Ocean (NEMO v3.1.1; Madec 2008), implemented within the European DRAKKAR framework (Barnier et al. 2007). It consists of a high-resolution ($1/10^\circ$) nest of the South Atlantic and western Indian Oceans (50°S–8°N; 70°W–70°E) hosted in a two-way nesting approach within a global base model with a nominal horizontal resolution of 0.5° . The horizontal refinement is performed with the Adaptive Grid Refinement in Fortran (AGRI; Debreu and Blayo 2008). The model has 46 vertical levels of variable thickness with highest resolution in the top 500 m. It is forced at the surface with momentum, heat, and freshwater fluxes from the Co-ordinated Ocean–Ice Reference Experiments (CORE) version 2b dataset (Large and Yeager 2009) utilizing a bulk forcing methodology.

The following experiments are considered in this study: (i) a hindcast simulation forced with an inter-annually varying atmosphere for the time period 1948–2007, (ii) a 60-yr climatologically forced experiment [reference experiment (REF; years 1–60)], and (iii) a 30-yr sensitivity experiment (also under background climatological forcing) in which the Southern Hemisphere westerlies are increased by 40% over the region from 0° to 35°E and from 34° to 45°S (LOCAL; years 31–60) to effectively simulate an isolated increase in Agulhas leakage (Durgadoo et al. 2013). The 40% wind stress increase was linearly ramped up within year 31. The LOCAL sensitivity experiment is considered in parallel with the last 30 years of the REF experiment. A more detailed description of the model and its experiments can be found in Durgadoo et al. (2013).

c. Methods

All trends are calculated as linear trends from monthly data over the given time period and expressed as an increase (decrease) per decade. To account for model drift, the linear trend of the climatological experiment REF—which mainly consists of a slight cooling of up to $0.06^\circ\text{C decade}^{-1}$ in the upper 50 m and around $0.2^\circ\text{C decade}^{-1}$ between 50- and 100-m depth in

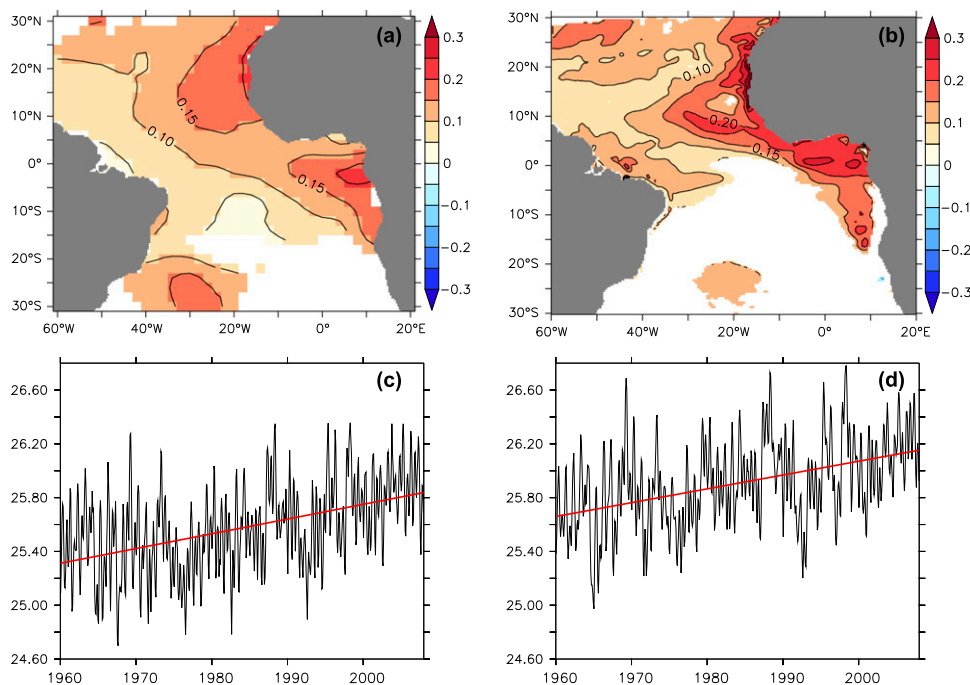


FIG. 1. (top) SST trends ($^{\circ}\text{C decade}^{-1}$) from (a) NOAA ERSST data and (b) the model hindcast experiments for 1960–2007. Only trends significant at the 95% level according to a Student's t test are shown. (bottom) SST averaged over 20°S – 30°N and 60°W – 15°E , with the linear trend overlaid in red, from (c) NOAA ERSST data and (d) the model hindcast simulation.

the equatorial Atlantic—is subtracted from the hindcast experiment before calculating the trend of the latter. To infer which changes are due to increased Agulhas leakage transport, we analyze differences between the sensitivity run LOCAL and the climatological control experiment REF.

For a Lagrangian trajectories analysis, a large number of particles $O(10^5)$ are released within the nested domain of the REF and LOCAL experiments across the Agulhas Current at 32°S in the Indian Ocean (a 300-km section from the coast over the full depth of the poleward flowing current) every 5 days for the first 10 years of each experiment (years 31–40). They are then integrated over the years 31–60 of the experiment using the ARIANE software (Blanke et al. 1999). For the analysis, the trajectories are first subsampled to keep only those that cross 10°S in the Atlantic $O(10^4)$ and then gridded onto $0.5^{\circ} \times 0.5^{\circ} \times 10\text{ m}$ boxes. Water properties, such as temperature, salinity, and density, at every time step of individual trajectories are assigned from the simulated in situ properties.

An integrated transport is calculated from the Lagrangian particles by the use of the modeled trajectories and the associated individual transports T_n , following the method described by Blanke et al. (1999): Each crossing of a trajectory through a junction of two

model grid cells is recorded on the corresponding velocity grid point. The associated transports T_n are summed up algebraically, whereby northward, eastward, and upward crossings are counted positive, while southward, westward, and downward crossings are counted negative. The resulting three-dimensional cumulative transport field T is further integrated zonally and vertically from the bottom to the top.

3. Results

a. Temperature trends in the tropical Atlantic

Since the 1960s, a general warming trend of up to $0.2^{\circ}\text{C decade}^{-1}$ at the sea surface has been observed in the tropical Atlantic Ocean (Figs. 1a,c; cf. Servain et al. 2014). A recent study by Karl et al. (2015) on biases in temperature data suggests that the trend might be even larger. It is most pronounced in the eastern part of the basin along the African coast, in particular in the northeastern and southeastern coastal upwelling regions (Fig. 1a). Averaged over the tropical Atlantic from 20°S to 30°N and 60°W to 15°E , the trend amounts to $0.11^{\circ}\text{C decade}^{-1}$ (Fig. 1c). According to a Student's t test, this trend is significant at the 99% level. The hindcast ocean model simulation mostly captures the

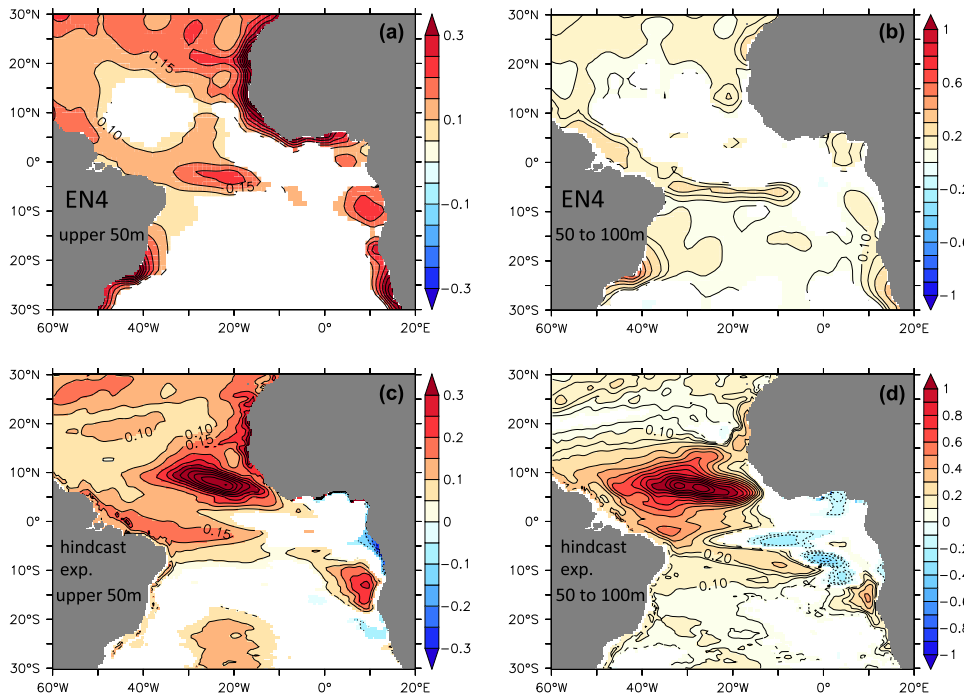


FIG. 2. Temperature trends ($^{\circ}\text{C decade}^{-1}$) (left) for the upper 50 m and (right) at 50–100-m depth from (a),(b) EN4 and (c),(d) the model hindcast experiment for 1960–2007. Only trends significant at the 95% level according to a Student's t test are shown.

observed trend, both in amplitude ($0.10^{\circ}\text{C decade}^{-1}$ averaged over the tropical Atlantic; Fig. 1d) and spatial characteristic (Fig. 1b), except for the region south of 5°S directly at the African coast. The agreement between the forced ocean model and observations in SST can be expected as the forcing methodology implies a damping of the model SST toward the prescribed atmospheric temperatures. However, the model fields together with the objectively analyzed EN4 dataset allow us to evaluate also subsurface temperature trends (Fig. 2). Consistent with findings by Servain et al. (2014) from mooring data of the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) at 8°N , 38°W that the warming there was especially large at about 100-m depth, we find the strongest warming trend in the model at about 5° – 10°N in 50–100-m depth (Fig. 2d), while the warming is weaker or not significant in the EN4 data (Fig. 2b). Long time series of subsurface temperature observations are sparse in the tropical Atlantic but also the subsurface trends calculated from EN4 data suggest that the warming is not only confined to the surface. Averaged over the upper 50 m, we find the strongest warming in the coastal upwelling regions and also along the equator and at the western boundary (Fig. 2a). Trends are weaker between 50- and 100-m depth, but the general pattern remains similar (Fig. 2b). The hindcast experiment shows roughly consistent trends but a much stronger warming between 5°

and 15°N . We note that the trend in EN4 is not significant in large areas, especially where we find the largest discrepancy between model and data (i.e., north of the equator). In light of the large uncertainties of the EN4 dataset at 50–100-m depth, we can mainly conclude that the warming trend observed in SST is also reflected below the mixed layer.

Mechanistically, a strong warming below the mixed layer would lead to an increased SST because of upwelled waters being warmer. This process should be sustained by the enhanced wind stress. In agreement with Servain et al. (2014, their Fig. 8) the magnitude of wind stress averaged over the tropical Atlantic slightly increases in the model hindcast simulation from the 1960s to the 2000s (not shown). This increase manifests itself in particular in an intensification of the southeasterly trade winds south of the ITCZ over this time period (Fig. 3b). We also see some enhancement of the northeasterly trades north of the ITCZ in the western part of the basin, while the trend is less clear and mostly not significant in the eastern part. Consistent with this change in the wind stress field, we find an indication for enhanced upwelling just north of the equator and in the southeastern part of the basin from the trend in Ekman pumping (calculated as wind stress curl divided by the Coriolis parameter), while upwelling appears to have decreased directly at the coast between 5° and 15° in

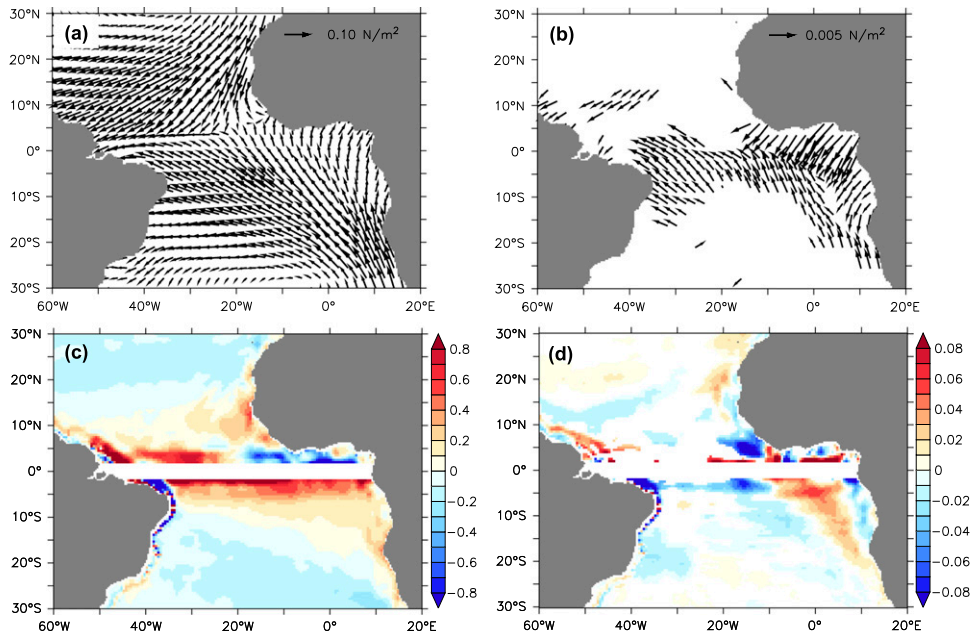


FIG. 3. (left) Mean and (right) trends per decade of (a),(b) wind stress (N m^{-2}) and (c),(d) Ekman pumping (cm s^{-1}) from the model hindcast experiment for 1960–2007. Positive values in (c),(d) denote upwelling; negative values denote downwelling. Only trends significant at the 95% level according to a Student's t test are shown. Note that Ekman pumping cannot be calculated very close to the equator, where the Coriolis parameter f approaches zero.

both the Northern and Southern Hemisphere (Fig. 3d). We conclude that some of the observed warming directly at the African coast might be due to a decrease in upwelling there. The general increase in the trade winds, however, suggests that the basinwide (sub-) surface warming seen in both observations and model (Figs. 1, 2) cannot be explained by regional wind changes. A sub-surface warming could, however, be communicated to the surface by increased upwelling in parts of the basin.

In the following, we seek to address the question of whether the warming of tropical Atlantic (sub-) surface waters can be related to an enhanced transport of Indian Ocean waters into the Atlantic.

b. Effect of increased Agulhas leakage on temperatures in the tropical Atlantic

Concurrent to the tropical Atlantic warming, Agulhas leakage—estimated using an established method (Durgadoo et al. 2013; Biastoch et al. 2009)—has increased by about 45% from roughly 13 Sv ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$) in the early 1960s to roughly 19 Sv in the early 2000s in the hindcast experiment (Fig. 4a). This increase is related to increasing wind stress over the Southern Ocean (Durgadoo et al. 2013).

The hindcast simulation alone does not allow us to conclusively distinguish (and quantify) the contribution of Agulhas leakage to the tropical Atlantic warming

from other factors because other components of the circulation are also changing in response to the interannual nature of the forcing. Therefore, the sensitivity experiment is used in order to isolate the contribution of Agulhas leakage. The experiments LOCAL and REF were both forced with climatological fields and pairwise contain no inherent trends. On average, Agulhas leakage in LOCAL is significantly higher at the 99% confidence level by 2.4 Sv compared to REF over the entire 30-yr period, corresponding to a sustained increase of about 15% [Fig. 4b; see also Durgadoo et al. (2013, their Fig. 7)]. A large fraction of this additional inflow reaches the equatorial region within the first two decades (Durgadoo 2013; Rühls et al. 2013). Following the increased inflow of warm Indian Ocean water, temperatures in the upper tropical Atlantic increase in the sensitivity experiments compared to REF (Figs. 5a,b). The warming is strongest between 15° and 5° S at a depth between 50 and 500 m but encompasses most of the tropical Atlantic between 15° S and 10° N down to 1000 m. Note that changes directly at the surface are difficult to assess, as they tend to be damped because of the forcing methodology. Even though no SST restoring is applied, the use of bulk formulas slightly damp the modeled SST toward the prescribed atmospheric temperature, which, in the case of REF and LOCAL, is climatological (i.e., the same for

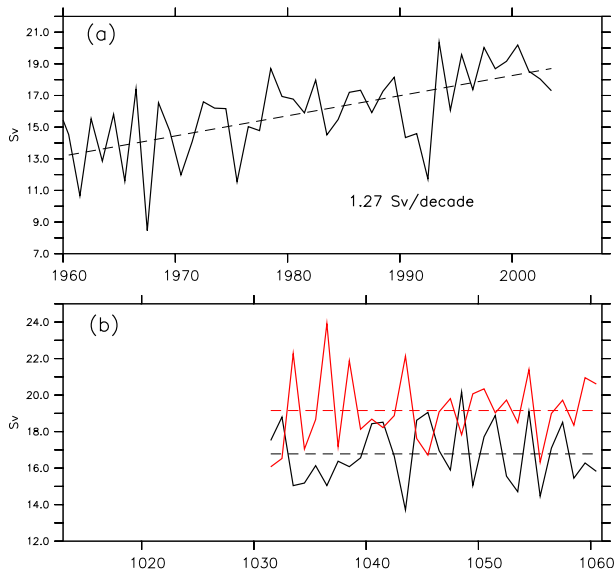


FIG. 4. Time series of Agulhas leakage transport (Sv) (a) from model hindcast simulation (solid line) with the linear trend overlaid (dashed) and (b) from climatological control experiment REF (black) and LOCAL (red). Averaged over years 1030–1060 (dashed lines), Agulhas leakage transport is 16.8 Sv in REF and 19.2 Sv in LOCAL. The climatological trend has been removed from the time series.

every year). The temperature at the surface can thus not respond to the subsurface warming introduced by changes in Agulhas leakage transport. The temperature difference between LOCAL and REF increases from

decade to decade (not shown). An average over the last decade of the integration (i.e., 20–30 years after the start of the wind increase) shows positive anomalies of up to 0.3°C (Figs. 5a,b). This is on the same order as the observed and simulated (by the hindcast experiment) SST and subsurface temperature trends per decade (Figs. 1,2). While many of the features are similar (e.g., the warming between 10° and 20°S at the eastern boundary that spreads toward the west) there are clearly differences between the patterns in Figs. 2d and 5b, indicating that Agulhas leakage cannot explain the whole warming trend in the hindcast experiment. An interesting feature is that the warm anomaly in the South Atlantic mainly follows the $\sigma_0 = 27.1$ isopycnal, which is the isopycnal corresponding to Antarctic Intermediate Water (AAIW; not shown). This is consistent with Schmidt and Johnson (2012), who attributed a warming of the AAIW core between 30° and 20°S to increased Agulhas leakage via changes in the southern annular mode (SAM) index, and with McCarthy et al. (2011), who showed that a salinification of the AAIW layer has its origin in the Indian Ocean. It is important to note that half of the AAIW immediately west of the Agulhas retroflexion has its origin in the Agulhas Current (Biastoch and Böning 2013).

The increase in tropical Atlantic temperatures that follows the strengthening of Agulhas leakage transport is accompanied by an increase in Atlantic heat content (Fig. 6). Tropical Atlantic heat content anomalies

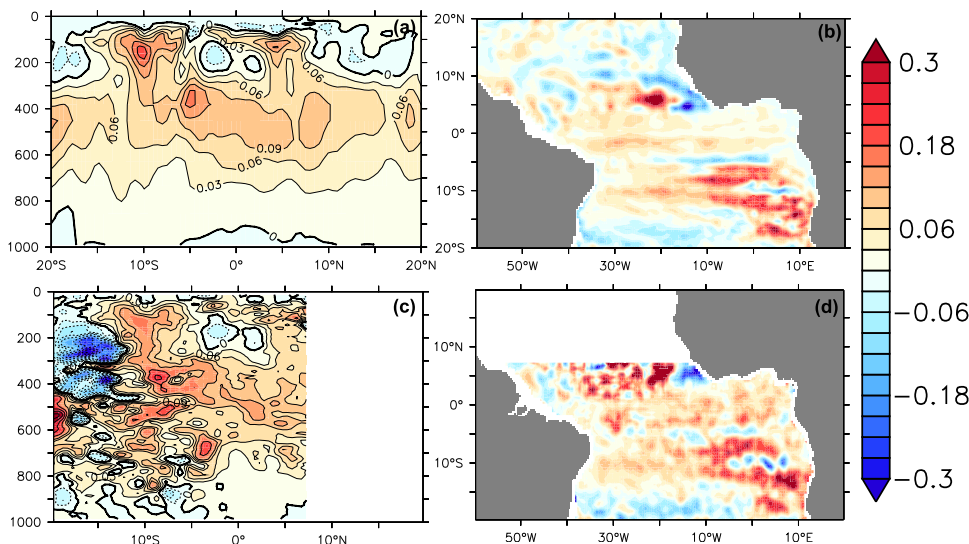


FIG. 5. Temperature difference (averaged over years 51–60) between sensitivity experiment with artificially increased Agulhas leakage (LOCAL) and control simulation (REF) from (top) Eulerian and (bottom) Lagrangian fields: (a),(c) as a function of depth and latitude averaged across Atlantic basin; (b),(d) averaged over 50–100-m depth. Note that the Lagrangian analyses were performed within the high-resolution nest of INALT01, where the northern boundary is 8°N .

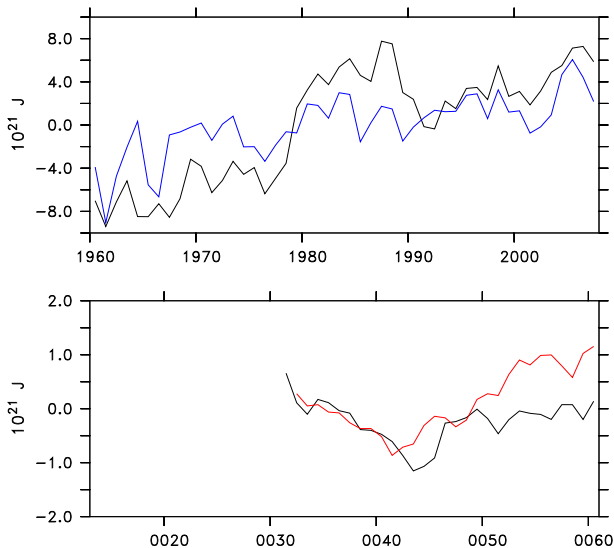


FIG. 6. Atlantic heat content anomalies for the upper 300 m between 20°S and 10°N from (top) the hindcast experiment (black) and EN4 (blue) and (bottom) REF (black) and LOCAL (red).

integrated between 20°S and 10°N and the upper 300 m of the water column increase by about 1×10^{21} J in LOCAL compared to REF about 10–15 years after the 2.4-Sv increase in leakage started. In the EN4 data, we find a heat content increase of about 7×10^{21} J from the 1960s to early 2000s. The increase is even larger in the hindcast experiment, where it amounts to about 11×10^{21} J, which corresponds to a leakage increase over the same time period of roughly 6 Sv. A simple scaling argument would suggest that this 6-Sv leakage increase in the hindcast would induce a heat content change of 2.5×10^{21} J (in LOCAL), which is about 23% of the total hindcast increase. Note that this assumes a quasi-instantaneous and sustained increase in leakage in the hindcast, which Fig. 4 shows is not the case. Nonetheless, this allows us to provide an upper-bound quantitative estimate of the impact of increased leakage on tropical Atlantic upper-ocean heat content.

c. Lagrangian analysis

To assess the pathways water takes from the Agulhas region, and to evaluate whether the warming trend in the tropics seen in Figs. 5a and 5b can indeed be traced back to waters coming directly from Agulhas leakage, a Lagrangian analysis is performed. As described in section 2, particles are released within the Agulhas Current in REF and LOCAL, and the trajectories are subsampled to analyze only those that cross 10°S in the Atlantic. The pathways of the trajectories from REF are depicted in Fig. 7a. They look very similar in LOCAL (not shown). Consistent with the findings of Rühls et al.

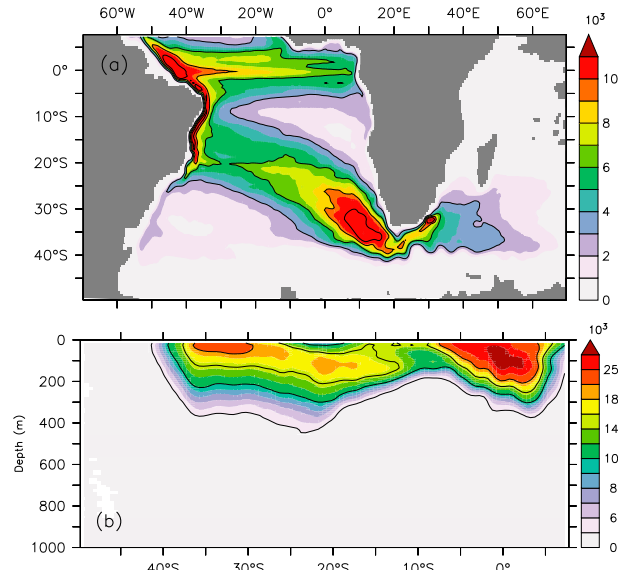


FIG. 7. Particle counts per $0.5^\circ \times 0.5^\circ \times 10$ m grid box: (a) vertical sum and (b) zonal sum for the Atlantic basin, illustrating the preferred pathways of Lagrangian particles from Agulhas leakage that cross 10°S in the reference experiment (REF). Contour intervals are (a) 3×10^3 and (b) 5×10^3 .

(2013), the particles that reach the tropical Atlantic mainly follow a direct route to the western boundary and enter the equatorial zonal current system. It is noteworthy that the region in which we find the strongest warming in LOCAL compared to REF (Fig. 5b) corresponds to this direct pathway (Fig. 7a). Floats can be found over most of the upper 1000 m, but they are concentrated in the upper 300 m (Fig. 7b).

Latitude–depth sections, as well as maps at 50–100-m depth of the difference in temperature between REF and LOCAL from the Lagrangian float information (Figs. 5c,d), are compared to the Eulerian field (Figs. 5a,b) to figure out which part of the Eulerian temperature difference is due to waters coming directly from Agulhas leakage. While there are some differences in the patterns, in particular between 200 and 400 m south of about 12°S, the structure and amplitude agree very well, suggesting that most of the tropical Atlantic warming seen in LOCAL can indeed be attributed to the increased inflow through Agulhas leakage.

The Lagrangian integrated transport (Fig. 8) reveals that Agulhas leakage waters contribute about 6 Sv to the waters upwelled at the equator as part of the basinwide Atlantic meridional overturning circulation in the reference experiment (Fig. 8a). In the sensitivity experiment, this contribution is enhanced by about 0.5 Sv (Fig. 8b). This increase is consistent with a strengthening of the Agulhas water contribution to the North Brazil Current (NBC) by 0.6 Sv in LOCAL compared to REF

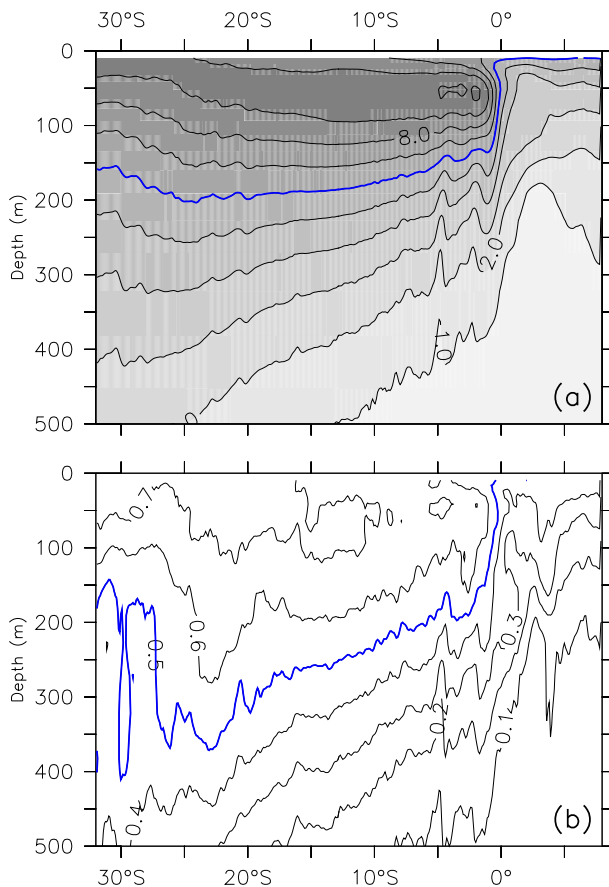


FIG. 8. Integrated transport for the Atlantic basin (integrated from bottom to top) calculated from Lagrangian particles released in the Agulhas region from (a) REF and (b) the difference between LOCAL and REF.

(Durgadoo 2013). The upwelling of Agulhas leakage waters at the equator provides a link between the warming of the waters below the mixed layer seen in the sensitivity experiments and the observed SST increase in the tropical Atlantic upwelling regions.

4. Discussion and conclusions

Over the last decades, an increase in SST has been observed in the tropical Atlantic Ocean and in particular in the eastern equatorial and coastal upwelling regions, despite stronger upwelling-favorable winds. In the present study, model experiments have been used to investigate whether increased inflow of warm Indian Ocean waters through Agulhas leakage has contributed to that warming. A hindcast simulation in which Agulhas leakage increases by about 45% from the 1960s to the early 2000s captures the observed warming trend and suggests—in accordance with trends from observed

EN4 subsurface temperature data—that the warming trend in the tropical Atlantic is not restricted to the surface but is present below the mixed layer as well. The warming signal that is found in the upper tropical Atlantic Ocean in a sensitivity experiment with artificially increased Agulhas leakage compared to a control simulation indicates that the warming seen in the hindcast experiment and observations can partly be attributed to an increased inflow of warm Indian Ocean water. This view is supported by a Lagrangian analysis in which temperature differences were calculated exclusively from particles of Agulhas origin.

As SST is damped toward prescribed atmospheric temperatures in this forced ocean model, it is difficult to assess temperature changes at the sea surface. However, the clear warming of subsurface waters that is seen in the model run with increased Agulhas leakage compared to the control simulation in both the Eulerian (Figs. 5a,b) and Lagrangian (Figs. 5c,d) view should, in the real world, be connected to an increase in SST through the upwelling of those warmer subsurface waters. The trend in Ekman pumping calculated from the wind stress curl of the hindcast experiment suggests that upwelling is indeed increased just north of the equator and in the southeastern part of the basin (Fig. 3d). The Lagrangian integrated transport (Fig. 8) confirms that waters of Agulhas origin contribute to the equatorial upwelling and that this contribution is enhanced when Agulhas leakage increases.

The information we can obtain from the climatological sensitivity experiments do not allow for an exact quantification of the Agulhas leakage contribution to the observed warming trend in the tropical Atlantic since the 1960s as we do not know the real world Agulhas leakage increase over the past decades. Also, the difference between the sensitivity and the climatological reference experiment over a decade cannot be directly compared with a long-term trend. Our results suggest, however, that an idealized 15% increase of Agulhas leakage is associated with subsurface temperature changes in the tropical Atlantic on the order of 0.3°C. Changes in Agulhas leakage transport are thus likely an important component of the tropical Atlantic warming trend, suggesting that remote forcing from the South Atlantic can help to explain the seemingly inconsistent trends of SST and local winds in the eastern equatorial and coastal upwelling regions of the tropical Atlantic Ocean.

While we can conclude from our results that the increase in Agulhas leakage in the last decades has contributed to the warming trend in the tropical Atlantic, it cannot explain the whole extent and structure of the observed SST trend. Other mechanisms must thus have

played a role as well. In general, all processes that lead to warming below the mixed layer would allow the surface to warm even in the face of stronger upwelling due to the strengthened trade winds. These processes could be more local than the influence of Agulhas leakage (e.g., related to changes in the subduction regions in the subtropics that are connected to the equatorial and coastal upwelling sites via the subtropical–tropical cells) (e.g., Schott et al. 2004). It is also important to note that there is considerable uncertainty regarding the magnitude and spatial patterns of the trade wind increase among wind products. Understanding all the processes that have contributed to the tropical Atlantic warming trend over the last decades will be an aim for further studies.

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